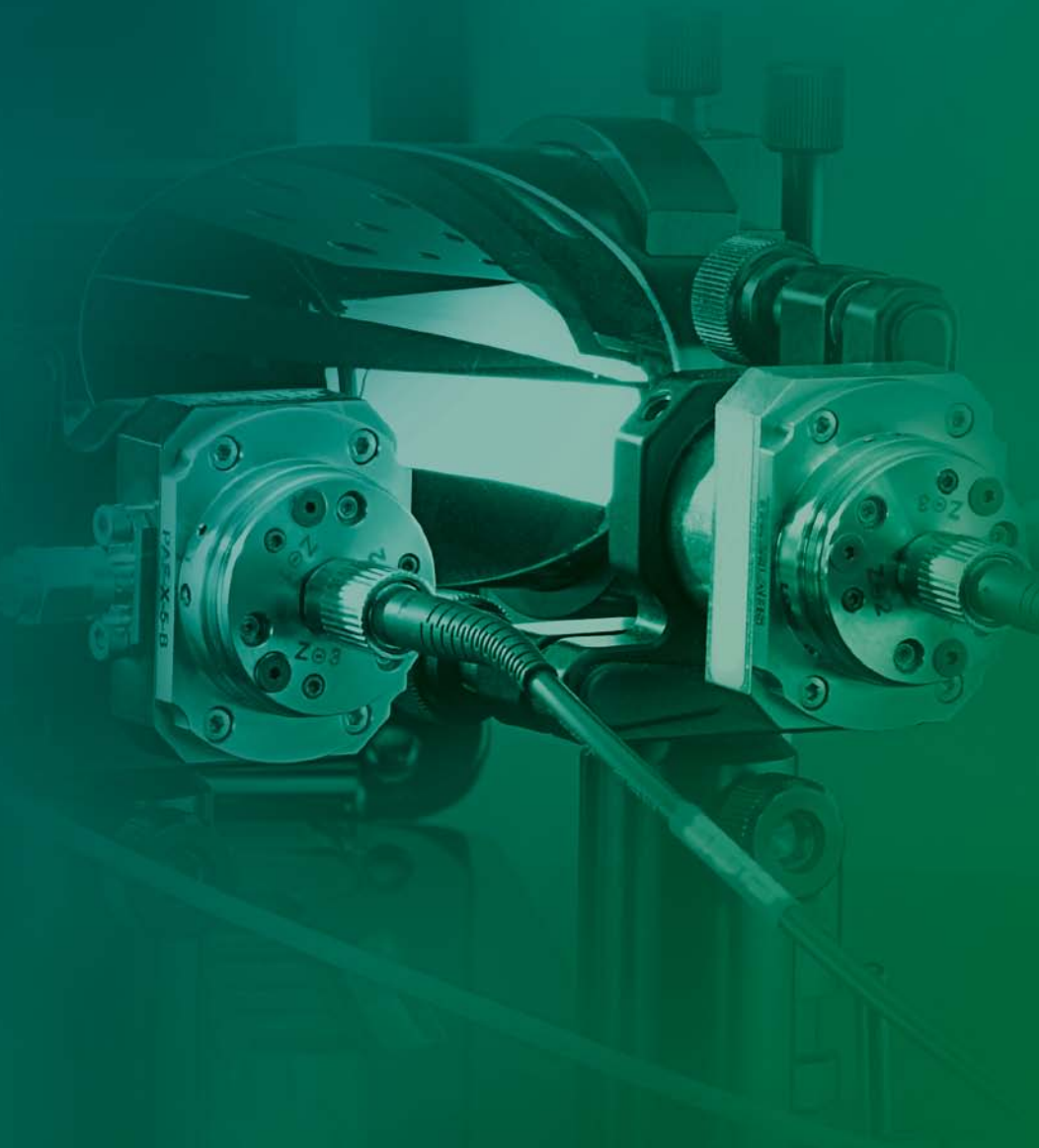




# Terahertz Spectrometers



## Basic Operation Principles

The terahertz (THz) and sub-THz frequency region (100 GHz – 10 THz) of the electromagnetic spectrum bridges the gap between the microwaves and infrared. THz waves penetrate dielectric materials like paper or plastic, are reflected by materials with free electrons like metals and are absorbed by molecules with certain vibration levels within the terahertz band. Terahertz absorption or reflection spectroscopy, imaging of biological and other objects, THz tomography, and optical pump-THz probe spectroscopy are all hot topics in recent scientific conferences with possible applications in semiconductor, medical and security industries.

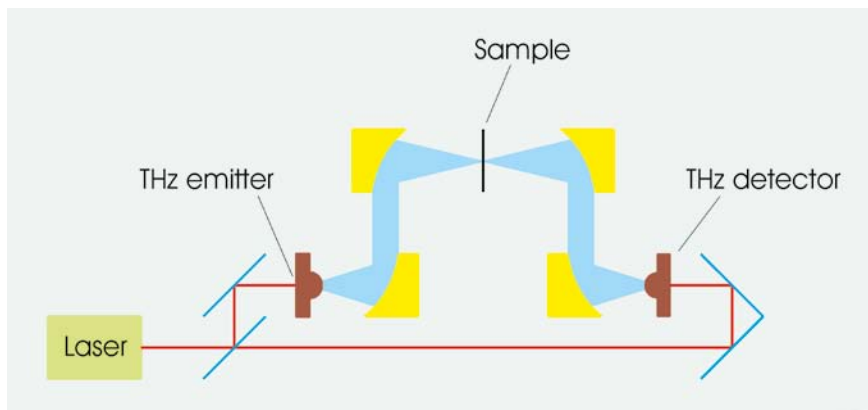
One of the most common method of coherent THz generation and detection is approached in terahertz time-domain spectroscopy (THz-TDS) setup. It consist of femtosecond laser, optical delay line and two photoconductive antennas operating as THz emitter and detector. Sub-picosecond pulses of THz radiation are detected after propagation through a sample and an identical length of a free space. A comparison of the Fourier transforms of these pulse shapes gives the absorption spectra of the sample under investigation.

### THz-TDS TECHNOLOGY ADVANTAGES

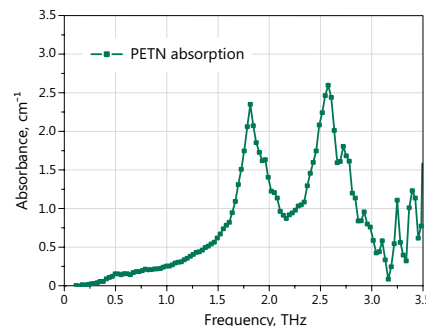
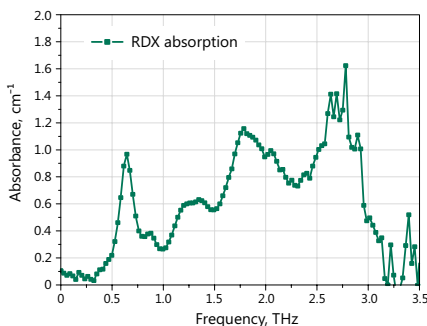
- ▶ Broadband spectral coverage in THz range
- ▶ High dynamic range
- ▶ Complete amplitude and phase detection
- ▶ Picosecond time resolution
- ▶ Optical pump-THz probe experiment possibility

### APPLICATIONS AREAS

- ▶ Material characterization
- ▶ Non-destructive testing
- ▶ Pharmaceutical industry
- ▶ Medical imaging
- ▶ Homeland security
- ▶ Semiconductor industry



Simplified scheme of THz time-domain spectroscopy setup



Absorption spectra of explosives in terahertz range measured by Ekspla T-SPEC spectrometer

## Real-Time Terahertz Spectrometer



Real-time Terahertz Spectrometer offered by Ekspla is a powerful tool for investigative applications of pulsed terahertz waves. With simple and robust design, it is easy-to-use and adaptable to individual requirements.

The unique design of microstrip photoconductive antenna fabricated on low-temperature grown GaAs substrate ensures broadband spectral coverage and high dynamic range. The system is designed with two delay lines: fast and slow. Fast scan line allows real time data acquisition with 10 spectra/s speed and 116 ps time window. Average of collected spectra can increase dynamic range up to 90 dB at pulse maximum and extend spectral range up to 5 THz. Additional slow delay line allows combination of multiple time windows;

thus spectrometer obtains excellent spectral resolution up to 1 GHz. The fast scan line is designed without bearings and uses a magnetically coupled drive which makes it extremely reliable and significantly extends the lifetime.

T-SPEC spectrometer has housing with mounted gas inlets. It can be used as purging box, when experiment requires special environmental conditions, like nitrogen or dried air. The spacious sample area allows easy integration of additional equipment, like cryostat or heater. On a special demand we can provide the integration of such equipment, ensuring good fit, spectrometer box sealing, vibration isolation and operation automation.

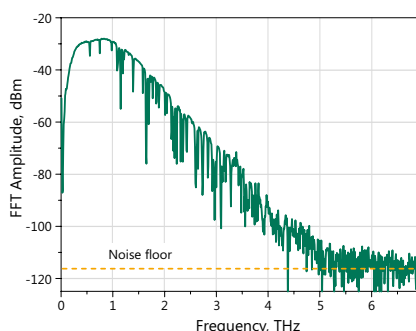
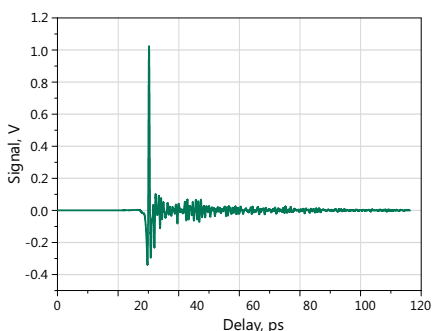
## T-SPEC series

### FEATURES

- ▶ *Wide spectral range up to 5 THz*
- ▶ *High dynamic range >90 dB @ 0.4 THz*
- ▶ *Real-time data acquisition up to 10 spectra/s*
- ▶ *Excellent spectral resolution up to 1 GHz*
- ▶ *"No bearing" design of fast delay line – virtually unlimited lifetime*
- ▶ *Transmission and reflection modes*
- ▶ *High spatial resolution THz imaging*
- ▶ *Complete PC control*
- ▶ *User-friendly software*

### APPLICATIONS

- ▶ *Chemical material characterization*
- ▶ *Carrier lifetime and mobility in semiconductors*
- ▶ *Dielectric properties and complex refractive index*
- ▶ *Metamaterials investigation*
- ▶ *Medical and biological nondestructive research*
- ▶ *Thickness measurements*



Typical performance of T-SPEC series Real-time THz Spectrometer (measured in ambient atmosphere)

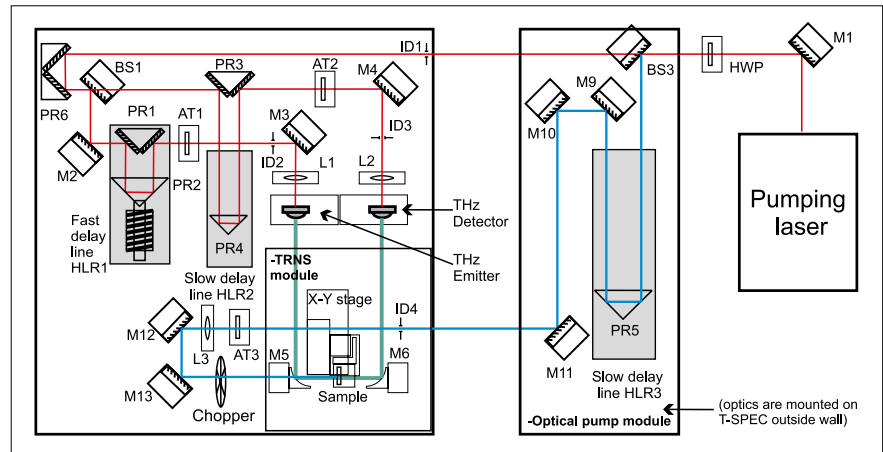
Spectrometer is equipped with two standard spectroscopy modules for transmission and reflection configurations. Each module contains motorized sample manipulator. This allows measurements of multiple samples one by one, without physical access to the spectrometer. Reflection module has convenient vertical architecture, where THz beams reaches the sample from bottom and reflects backwards. The measured samples can be replaced quickly just by laying them down on the sample holder. No adjustment is needed either when changing samples or when changing modules.

Our T-SPEC series spectrometer is the perfect choice for broadband THz imaging. It allows scan of up to 25×25 mm sample with spatial resolution of approx. 1 mm. Measurements contain information about the target, revealing both structural and spectroscopic information.

T-SPEC spectrometer can be adopted for optical pump THz probe measurements. This allows investigation of carrier dynamics in semiconductors, nanocrystals, and other materials. One part of additional optics is placed inside spectrometer; another part with delay line is mounted on T-SPEC outside wall. Measurement can be done up to 1 ns with temporal resolution of approx. 0.5 ps.

**SPECIFICATIONS**

Model	T-SPEC 800	T-SPEC 1000
<b>GENERAL SPECIFICATIONS</b>		
Spectral range	>4.5 THz	>3.5 THz
Dynamic range	>90 dB @ 0.4 THz	>70 dB @ 0.4 THz
Acquisition rate	10 scans/s	
Spectral resolution:		
fast scan	8.6 GHz	
combined mode (fast + slow)	~1 GHz	
Scan range:		
fast scan	116 ps	
combined mode (fast + slow)	928 ps	
Beam diameter on the sample	~ 2 mm @ 0.4 THz	
Configurations	Transmission / normal reflection	
Computer interface	USB 2.0	
Dimensions	560 × 520 × 202 mm	
<b>PUMP LASER REQUIREMENTS</b>		
Pump laser	Integrated ELMO with second harmonic module	Integrated FF50
Laser output type	Free space	
Wavelength	780 nm	1064 nm
Pulse duration	<100 fs	<160 fs
Output power	>80 mW	>60 mW
Pulse repetition rate	100 MHz	30 MHz



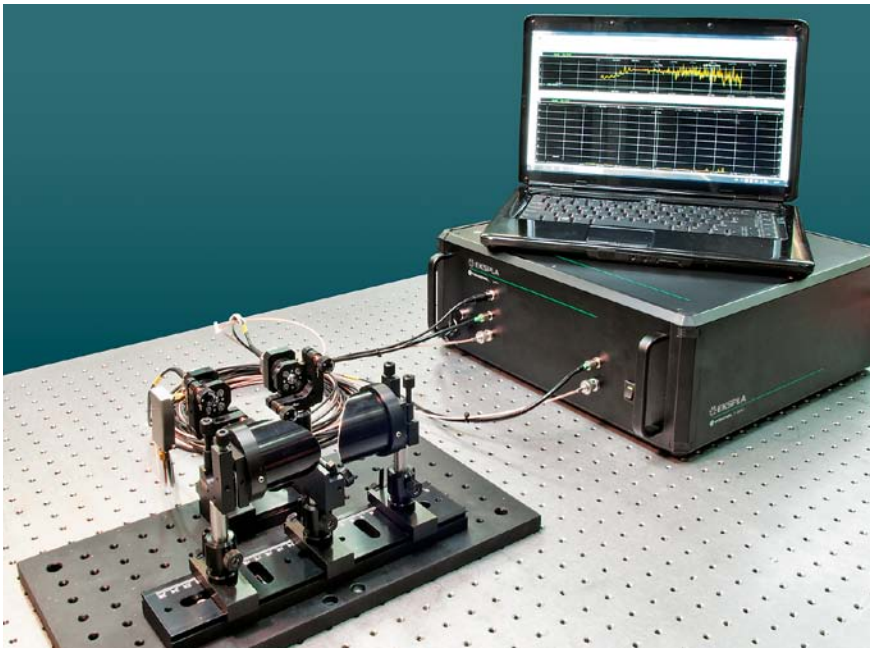
Optical layout of THz spectrometer T-SPEC series for optical pump THz probe measurements



T-SPEC spectroscopy modules: reflection geometry (left) and transmission geometry (right)

# Fiber-coupled Terahertz Spectrometer

# T-FIBER series



### FEATURES

- ▶ Pump pulse fiber delivery
- ▶ Real-time measurements
- ▶ Unlimited lifetime of delay line
- ▶ Flexible design
- ▶ THz imaging capability
- ▶ Complete PC control
- ▶ Excellent value for money

### APPLICATIONS

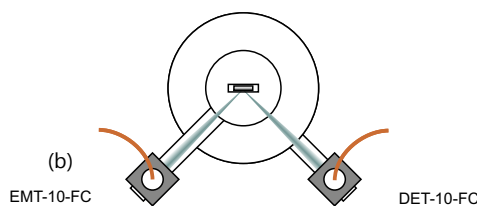
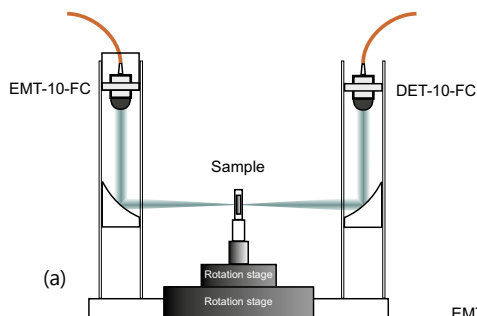
- ▶ Time-resolved broadband THz spectroscopy
- ▶ Production processes monitoring
- ▶ Hazardous substances detection
- ▶ Paint and coatings layers thickness measurements
- ▶ Food and agricultural products quality inspection
- ▶ Medical imaging

Fiber-coupled Terahertz Spectrometer T-FIBER, offered by Ekspla, features flexible and robust design. It has integrated femtosecond fiber laser with two fiber output ports. Comparing to common Ti:S oscillators, fiber lasers are smaller, cheaper, more reliable and feature parameters that are perfect for terahertz generation.

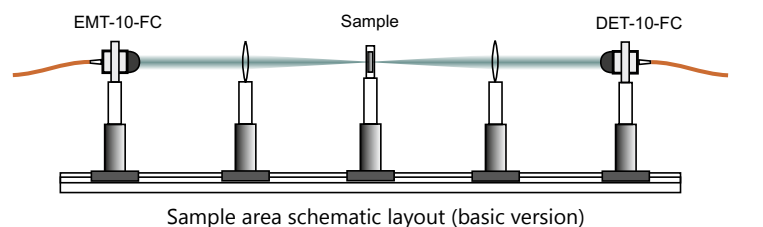
Femtosecond laser, delay line and signal registration electronics are integrated in a single compact housing with footprint only 40×40 cm. Minimal set of free space optics used in spectrometer allows stable long time operation. Special “no bearing” design of fast delay line makes its

lifetime practically unlimited. Delay line allows real time data acquisition with 10 spectra/s speed and 116 ps time window.

Fiber-coupled THz emitter and detector make switching between experiment geometries easier than before. Due to its compact size and reliability during transportation, T-FIBER spectrometer is dedicated for laboratory use as well as for real field applications. We are also happy to customize it according to special OEM customer requirements.



Goniometer schematic layout: side view (a), top view in reflection geometry (b), top view in transmission geometry (c)



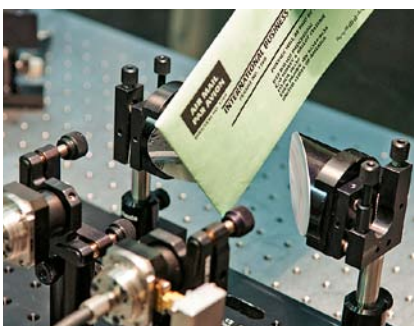
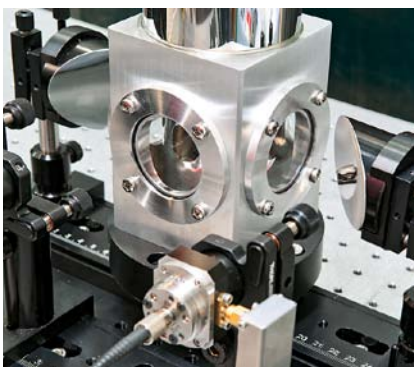
Basic setup of T-FIBER spectrometer includes optical rail, with fiber-coupled THz emitter, detector, two PE lenses and sample holder. This setup provides transmission geometry and it is extremely simple in alignment.

As an option goniometer stage can be supplied. This inexpensive module allows operation in multiple most common geometries, including transmission and tunable angle reflection from approx. 18.5° up to 90°. It also can be used for unique THz scattering experiments, because sample and detector angles can be changed independently. This module gives also better focusability of THz beam.

**SPECIFICATIONS**

Model	T-FIBER basic version	T-FIBER with goniometer
<b>GENERAL SPECIFICATIONS</b>		
Spectral range	>3 THz	
Dynamic range	>60 dB @ 0.4 THz	>65 dB @ 0.4 THz
Acquisition rate	10 scans/s	
Spectral resolution	8.6 GHz	
Scan range	116 ps	
Configurations	Transmission	Transmission / tunable angle reflection / scattering
Incidence angles range (in reflection mode)	–	18.5 – 90°
Detection angles (in scattering mode)	–	37 – 286°
Computer interface	USB	
Main unit dimensions	400 × 400 × 158 mm	
Spectroscopy setup footprint	670 × 70 mm	450 × 300 mm
<b>PUMP LASER</b>		
Model	LightWire FF50	
Laser output type	Fiber	
Wavelength	1064 nm	
Pulse duration	<160 fs	
Output power	>40 mW	
Pulse repetition rate	40 MHz	

**WE ARE HAPPY TO TAILOR OUR PRODUCTS FOR YOUR APPLICATION**



# THz Emitter and Detector for Free Space Coupling



THz emitter and THz detector consists of a microstrip photoconductive antenna (PCA) fabricated on GaAs substrate. Depending on pump laser wavelength either low temperature grown GaAs (LT-GaAs) or GaBiAs is used as photoconductor. On its surface a coplanar Hertzian type dipole antenna structure is formed using AuGeNi metallization. Photoconductive antenna geometry, as well as the properties of photoconductor epitaxial layers are optimized for highest THz radiation output efficiency, while preserving optimal bandwidth. As a result, typical emitted THz radiation power exceeds 10  $\mu$ W, when pumped by laser with 30 mW output power and <150 fs pulse duration. FWHM bandwidth of detection system exceeds 700 GHz with usable spectral range of 0.1–5 THz.

### FEATURES

- ▶ Based on LT-GaAs or GaBiAs photoconductive material
- ▶ Optimized for wavelengths around 800 nm or 1060 nm
- ▶ Wide spectral range and low noise
- ▶ Sub-picosecond temporal resolution
- ▶ Technical passport and test report included

### APPLICATIONS

- ▶ Time-resolved broadband THz spectroscopy
- ▶ Optical pump – THz probe spectroscopy
- ▶ THz imaging

THz emitter or detector is illuminated by laser beam from panel side. Laser beams must be focused between two electrodes (Fig. 1). The gap between metallic contacts is similar to laser spot diameter in detector case and larger – in emitter case. THz radiation is collected by integrated lens,

manufactured from high-density silicon, mounted on X-Y stage. EKSPLA offers two standard types of these lenses: for collimated or diverging THz beam output. In second case PCA is placed in aplanatic point of silicon lens, which reduces THz beam spherical aberrations. Adjustment

screws are used for Si lens positioning onto PCA center. SMA sockets on back side of the housing are used for connecting DC or AC bias to THz emitter and lock-in amplifier input to THz detector. Any of three M6 holes can be used for THz emitter mounting on optical table.

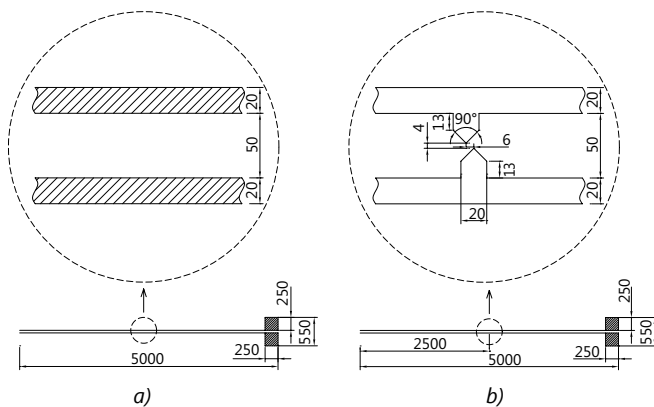


Fig. 1. Microstrip antenna drawings: (a) emitter, (b) detector

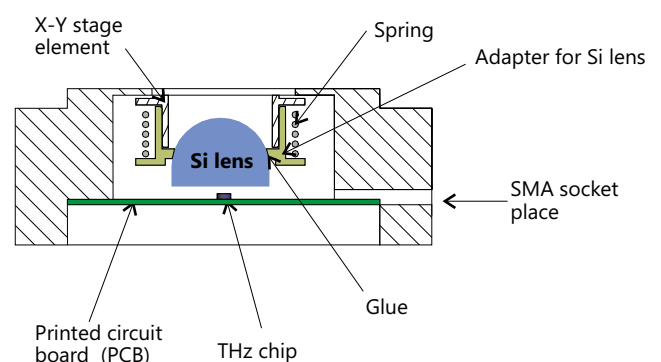


Fig. 2. THz emitter and detector cross-section

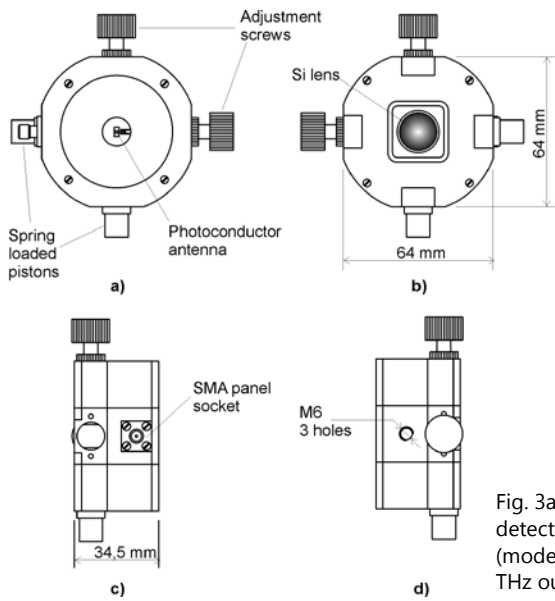


Fig. 3a. THz emitter/detector housing (model with collimated THz output)

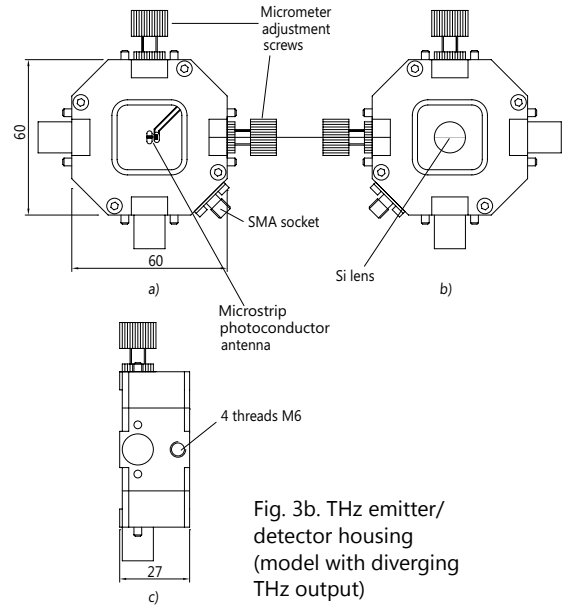


Fig. 3b. THz emitter/detector housing (model with diverging THz output)

SPECIFICATIONS <sup>1)</sup>

Model	Emitters		Detectors <sup>3)</sup>	
	EMT-08	EMT-10	DET-08	DET-10
<b>PHOTOCONDUCTIVE ANTENNA</b>				
Photoconductive material	LT-GaAs	GaBiAs	LT-GaAs	GaBiAs
Dimensions of the wafer	5 × 1.5 mm			
Thickness	600 μm			
Antenna type	strip line		dipole	
Bias voltage	50 V max, 40 V typical		±12 V	
Central THz frequency	~0.5 THz		0.5 THz	
Detected THz bandwidth	-		up to 5 THz	
<b>INTEGRATED FOCUSING LENS</b>				
Material	HRFZ-silicon			
Geometrical form	hyper-hemi-sphere			
THz beam output	collimated or diverging		-	
X-Y adjustable stage range	±3 mm			
<b>PUMP BEAM PARAMETERS</b>				
Excitation wavelength	800±40 nm	1060±40 nm	800±40 nm	1060±40 nm
Average power <sup>1)</sup>	<50 mW	<20 mW	<50 mW	<20 mW
Pulse duration	<150 fs			
Pulse repetition rate	20-100 MHz			
Beam profile	near to Gaussian			
Beam diameter <sup>2)</sup>	~2 mm			

<sup>1)</sup> Subject to laser pulse duration, repetition rate and beam size at the surface of wafer.

<sup>2)</sup> Recommended value, if used with EKSPLA THz emitter/detector mount of THz spectroscopy kit.

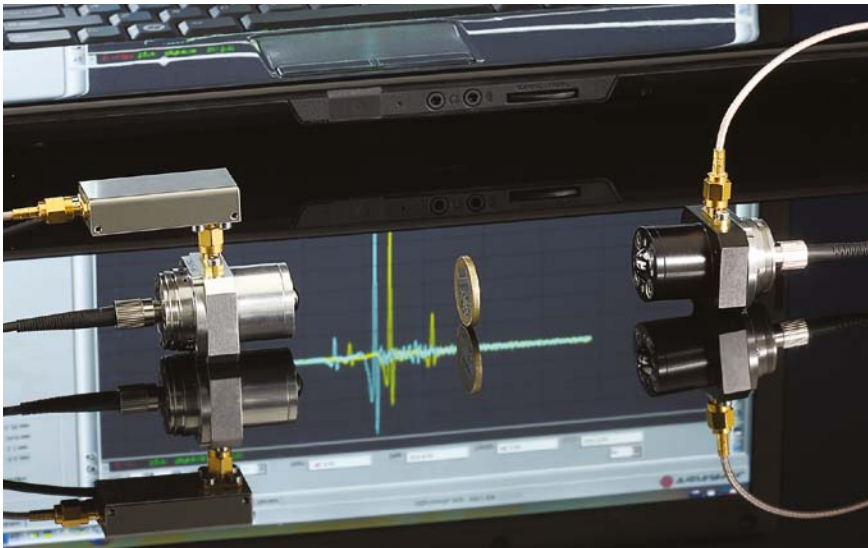
<sup>3)</sup> Integrated preamplifier.

ORDERING INFORMATION

Description	Model	Notes
THz emitter for 800 nm wavelength	EMT-8	Includes Si lens and coaxial cable with BNC connector
THz detector for 800 nm wavelength	DET-8	Includes Si lens and coaxial cable with BNC connector
THz emitter for 1060 nm wavelength	EMT-10	Includes Si lens and coaxial cable with BNC connector
THz detector for 1060 nm wavelength	EMT-10	Includes Si lens and coaxial cable with BNC connector
THz emitter/detector mounting stage	MNT	Includes pump beam focusing lens on XYZ stage
TMS-100M bias power supply	TMS-100	30–70 V DC or square-wave output



## Fiber-coupled THz Emitter and Detector



Fiber-coupled THz emitters and detectors offered by EKSPLA are designed for broadband operation and can be used in standard time-domain (THz-TDS) setup (Fig. 1).

housing compatible with standard 1" optical holders. Performance of each device is checked and technical passport, including testing report, is provided for customer.

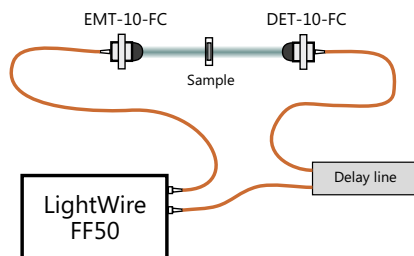


Fig. 1. THz time-domain spectroscopy setup

Unique GaBiAs material used in photoconductive antennas (PCA) features excellent sensitivity for wavelengths up to approx. 1060 nm and electron lifetime shorter than 1 ps. As a result ultra short half-cycle THz pulses with broad spectra up to 4 THz can be generated and detected. Pump beam fiber delivery eliminates time-consuming adjustments and ensures maximum flexibility of experiment. As an example, this feature allows fast and convenient switching between different geometries: transmission, reflection, etc. THz emitters and detectors are mounted into compact

### INTEGRATED SILICON LENS

THz emitters and detectors are supplied with integrated hyper-hemispherical lenses, made from high-resistivity silicon, attached to PCA to increase the radiation efficiency of THz waves into free space. EKSPLA offers two standard types of these lenses: for collimated or diverging THz beam output. Advantage of collimated THz beam output is simple setup, because no additional optical components between THz emitter and detector are required for experiment. However, this design features bigger spherical aberrations of THz beam, which affects focusing. In second case design of lens assumes positioning of the PCA in aplanatic point, which significantly reduces spherical aberrations. As a result nearly diffraction limited spot of THz beam can be achieved.

### FEATURES

- ▶ Based on unique GaBiAs photoconductive material
- ▶ Optimized for wavelengths around 1060 nm
- ▶ Technical passport and test report included

### APPLICATIONS

- ▶ Time-resolved broadband THz spectroscopy
- ▶ Optical pump-THz probe spectroscopy
- ▶ Suitable for all-in-fiber system solution

**PHOTOCONDUCTIVE ANTENNA (PCA)**

Photoconductive antennas are particularly designed for THz emitter or THz detector. The substrate of GaAs contains mesa-etched epitaxial active layer of GaBiAs in order to achieve high dark resistance. High photosensitivity of the material allows use of low average power optical pulses for excitation. On its surface a coplanar Hertzian type dipole antenna structure is formed using AuGeNi metallization (Fig. 2). The gap between metallic contacts is similar to laser spot diameter in detector case and larger – in emitter case. Photoconductive chip is mounted on PCB and placed inside metallic housing of device. SMA sockets on back side of the housing are used to connect DC or AC bias to THz emitter or lock-in amplifier input to THz detector.

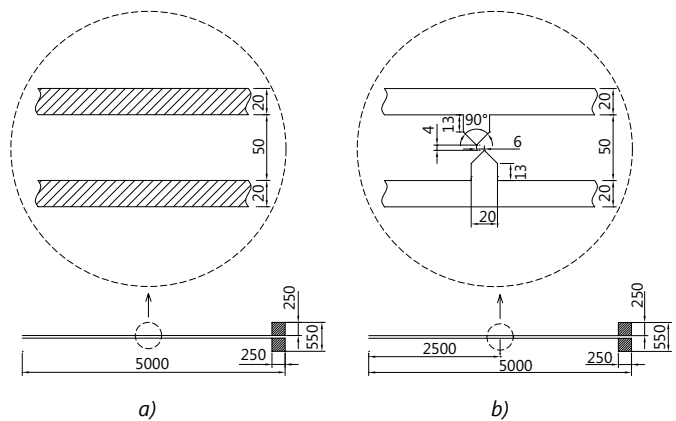


Fig. 2. Microstrip antenna drawings: (a) emitter, (b) detector (all dimensions are in micrometers)

**SPECIFICATIONS**

Model	Emitter EMT-10-FC	Detector DET-10-FC
<b>PHOTOCONDUCTIVE ANTENNA</b>		
Photoconductive material	GaBiAs	
Dimensions of the wafer	5 × 1.5 mm	
Thickness	600 μm	
Antenna type	strip line	dipole
Photosensitivity	up to 1100 nm	
Bias voltage	50 V max, 40 V typical	–
Detected THz bandwidth <sup>1)</sup>	–	>4 THz
<b>INTEGRATED FOCUSING LENS</b>		
Material	HRFZ-silicon	
Geometrical form	hyper-hemi-sphere	
THz beam output	collimated or diverging	–
<b>FIBER DELIVERY</b>		
Fiber length	3±0.2 m	
Fiber connector	FC/APC	
Wavelength <sup>2)</sup>	1064 nm	
Maximum optical pulse energy (on fiber input)	1 nJ (30 mW at 30 MHz)	
Recommended pump source	EKSPLA LightWire FF50 (with double output option)	

<sup>1)</sup> Pumped by 130 fs, 20 mW, 30 MHz pulses.

<sup>2)</sup> Other wavelengths are available on request.

**ORDERING INFORMATION**

Description	Model	Notes
Fiber-coupled THz emitter for 1060 nm wavelength	EMT-10-FC	Includes Si lens, optical fiber with FC/APC connector and coaxial cable with BNC connector
Fiber-coupled THz detector for 1060 nm wavelength	DET-10-FC	Includes Si lens, optical fiber with FC/APC connector and coaxial cable with BNC connector

**FIBER DELIVERY**

Standard configuration requires pre-chirped pulse with 0.5–2 ps duration on fiber input. Typically such pulse parameters are available directly from fiber lasers before compressor stage. In this case pulse is compressed while propagating through optical fiber with negative dispersion. Another solution can be applied for femtosecond pulses – near zero dispersion optical fiber. In such fiber femtosecond pulse keeps its form and pulse duration doesn't differ much on input and output of fiber. In both cases it works only for particular wavelength, so it should be specified while ordering. Laser radiation is delivered through FC/PCA fiber connector. It is focused onto PCA using lenses fixed inside the housing of THz emitter and THz detector.

## Terahertz Registration System TRS-16

Advanced electronics used in T-SPEC and T-FIBER terahertz spectrometers is also available as stand-alone product named TRS-16. It can be used for home-made opto-electronic or electro-optic pulsed THz spectroscopy systems. The complete set includes electronics module and fast scan delay line based on voice coil, with possibility to connect second slow delay line based on stepper motor. It also includes powerful software package used for system control and data acquisition. Similar version of dedicated software is also used in all Ekspla terahertz spectrometers.

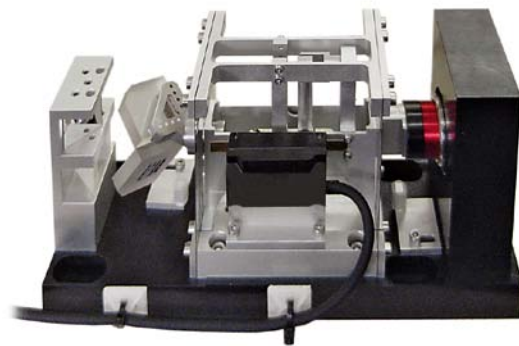
### ELECTRONICS

The electronic module of TRS-16 system consists of two main parts: delay lines control and signal registration. Fast delay line based on voice coil allows real time data acquisition at 10 scans/s rate with 116 ps scanning window. Use of the optical linear encoder ensures the extremely low jitter, thus registration system can achieve high dynamic range up to 90 dB. The registration part has embedded 16 bit analog to digital converter, operational preamplifier and the THz emitter bias modulator. TRS-16 system also provides bias for the photoconductive THz emitter in range from 10 to 95 V DC and for the operational preamplifier  $\pm 12$  V DC. Operational preamplifier is also included into the kit.



### MECHANICS

The fast scan delay line is designed without bearings and uses a magnetically coupled drive which makes it extremely reliable and significantly extends the lifetime. A special mechanical design makes movement of retroreflector straight along one axis, which results perfect beam pointing of the beam passing through the delay line. The maximum line scanning rate is matched with its resonance frequency. This feature substantially reduces energy consumption, vibrations and heat generation.



### SPECIFICATIONS

Analog to digital converter	16 bit
Detector antenna preamplifier gain	40 dB up to 300 kHz
Dimensions (LxWxH)	230 x 170 x 55 mm

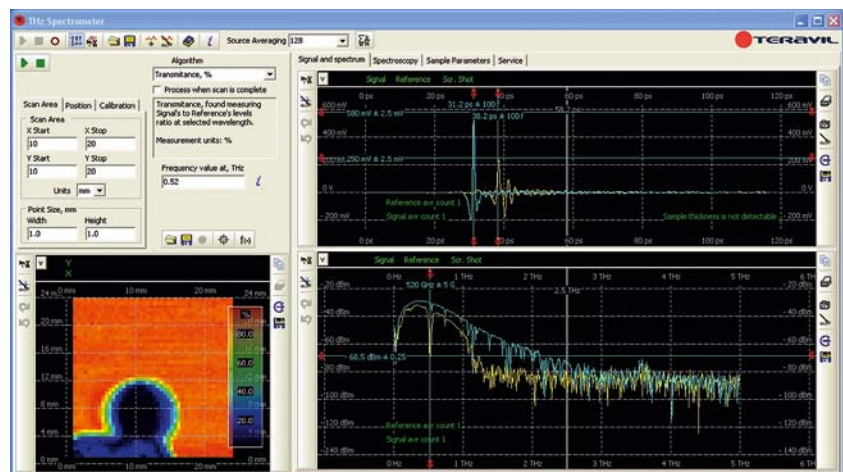
### SPECIFICATIONS

Maximum scan window	116 ps
Speed (at max scan window)	10 Hz
Dimensions (LxWxH)	214 x 75 x 120 mm

### SOFTWARE

The Terahertz Registration System TRS-16 comes with dedicated software capable to:

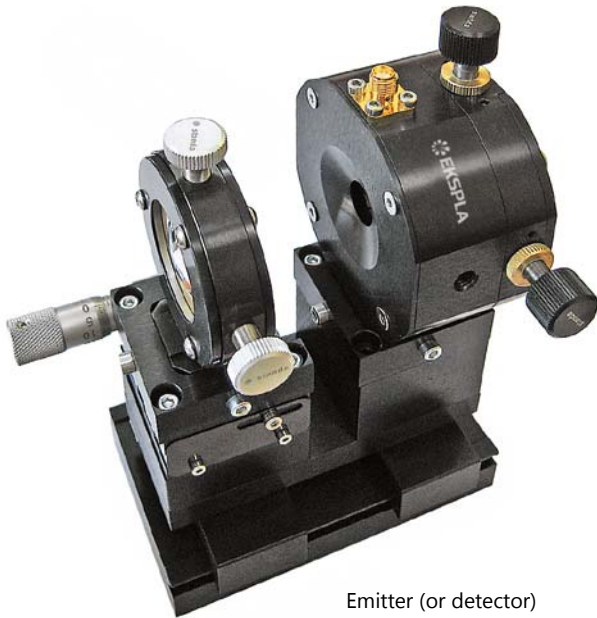
- ▶ register THz signal, get FFT spectrum, absorbance and transmittance in real time (10 scans/s);
- ▶ make a raster scan image using standard stepper motor XY stage;
- ▶ find the absorption, transmission and thickness of the sample;
- ▶ THz signal continuous data-flow recording;
- ▶ find complex index of refraction, complex conductivity and complex dielectric constant;
- ▶ register optical pump THz probe signal.



Raster scanning with Spectrometer 2D software

## Accessories

### THz EMITTER/DETECTOR MOUNTING STAGE



Emitter (or detector) mounted on its stage

Separately from THz emitter and detector EKSPLA provides convenient mounting stage compatible with both devices. It contains lens, mounted on adjustable XY holder, compact stage for shifting lens along optical axis and rail, on which both: lens and emitter/detector are mounted. This helps with pump beam guiding to the gap between electrodes located on photoconductive antenna, as well as adjusting beam diameter on active surface. Convenient fixing screws allow fast mounting and removing each part of this simple setup.

#### SPECIFICATIONS

Beam height	105 mm
X, Y axis travel range	3 mm
Z axis travel range	13 mm
Lens diameter	25.4 mm
Lens focal diameter	50 mm
Lens anti-reflection coating	AR/AR at selected wavelength (standard: 800 / 1030 / 1064 nm)

### BIAS POWER SUPPLY TMS-100 FOR THz EMITTER



Front view of TMS-100 power supply

#### FEATURES

- ▶ Low noise
- ▶ DC or square-wave output (needs external TTL input)
- ▶ Cable for connection to THz emitter included

#### SPECIFICATIONS

Square-wave modulation frequency	10 Hz – 100 kHz
Output voltage	30–70 V (adjustable)
Max current	1 mA
Output socket	BNC
Mains	100/220 V AC, 50/60 Hz
Dimensions (W×L×H)	130 × 190 × 39 mm

### OPERATIONAL PREAMPLIFIER FOR THz DETECTOR



External view of preamplifier

#### SPECIFICATIONS

<b>PREAMPLIFIER <sup>1)</sup></b>	
Preamplifier type	current-voltage converter
Conversion coefficient	> 10 <sup>6</sup>
Preamplifier head dimensions	60 × 12 × 15 mm
<b>POWER SUPPLY</b>	
Preamplifier power supply dimensions	155 × 65 × 80 mm
Preamplifier power supply output voltage	+ 15 V, - 15 V
Preamplifier power supply line voltage	220 V or 110 V

<sup>1)</sup> Preamplifier head is equipped with SMA connector matched with EKSPLA THz detector.

# THz Spectroscopy Kit

EKSPLA “THz spectroscopy kit” contains all the components necessary to build THz-TDS system. The standard kit consists of photoconductive antenna THz emitter and detector, pump laser beam guiding optics, motorized delay line with controller, bias power supply TMS-100, THz beam guiding optics, sample holder and lock-in amplifier. All components

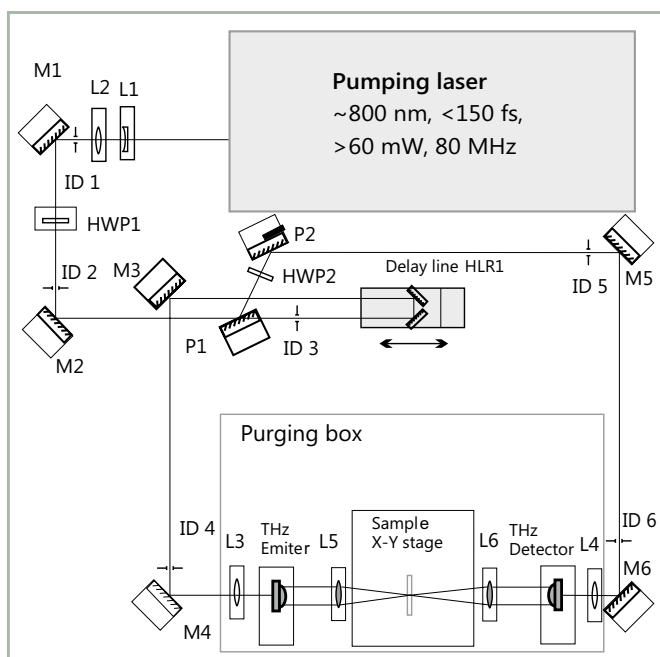
are assembled on the baseplate of 60×80 cm dimensions. Four standard configurations are available, optimized for transmission, reflection, imaging or pump-probe measurement. All can be easily interchanged and modified. Any other optional configuration can be ordered initially or as a future upgrade. THz spectroscopy kit is controlled by dedicated software.

### BASIC THz SPECTROSCOPY KIT INCLUDES:

- ▶ THz emitter and detector
- ▶ Pump laser beam guiding optics
- ▶ Motorized slow delay line with controller
- ▶ THz beam guiding mirrors
- ▶ Sample holder
- ▶ Lock-in amplifier
- ▶ Labview based software for data acquisition

### OPTIONAL ITEMS:

- ▶ Femtosecond laser
- ▶ Purging box, removes water absorption lines
- ▶ Motorized X,Y sample stage



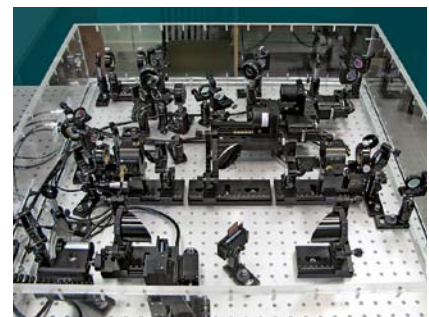
Optical layout of THz spectroscopy kit in transmission configuration

### OUR CUSTOM THz SYSTEMS EXAMPLES



LIDAR operating in terahertz range was used to scan remote objects at 7 m distance.

*THz LIDAR installed in Lomonosov Moscow State University, Russia*



Optical pump – terahertz probe spectroscopic technique allows investigation of carrier dynamics in semiconductors, nanocrystals, and other materials.

*Optical pump-THz probe system installed in The Institute of Physics, Chinese Academy of Sciences, Beijing, China*



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